Crystal Creek Dye Trace Report
Fillmore County, Minnesota

Traces:
March 11th 2010 (2), July 20th 2010 (2), November 15th 2010, March 17th 2011, November 3rd 2011 (3),
March 9th 2013 (2), March 30th 2013, April 21st 2016 (2)

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Introduction

Dye traces were conducted in and around the Crystal Creek Watershed in southern Fillmore County, Minnesota as part of the Environmental and Natural Resources Trust Fund (ENRTF) funded Springshed Mapping project. This report covers traces completed in 2010, 2011, 2013 and 2016.

The Root River Field to Stream Partnership is a multi-agency effort led by the Minnesota Department of Agriculture (MDA). The primary goal of the partnership is to characterize nutrient losses by agriculture to surface water and groundwater and to apply sustainable best management practices (BMPs) to reduce those losses. The Crystal Creek Watershed (CCW), one of the three intensive study areas in the partnership, is a 15 km2 (3,700 ac) watershed located in the Galena-Spillville karst of southeast Minnesota. In the CCW, 78% of the watershed land area is devoted to cropland with corn and soybeans making up 76% of the crop acres. Beginning in 2010, the Partnership has collaborated with the University of Minnesota-Department of Earth Sciences and the Minnesota Department of Natural Resources to conduct groundwater dye tracing within and around the CCW. Tracing was employed to delineate the areal extent of the groundwater springsheds which supply perennial flow to springs that discharge directly to Crystal Creek.

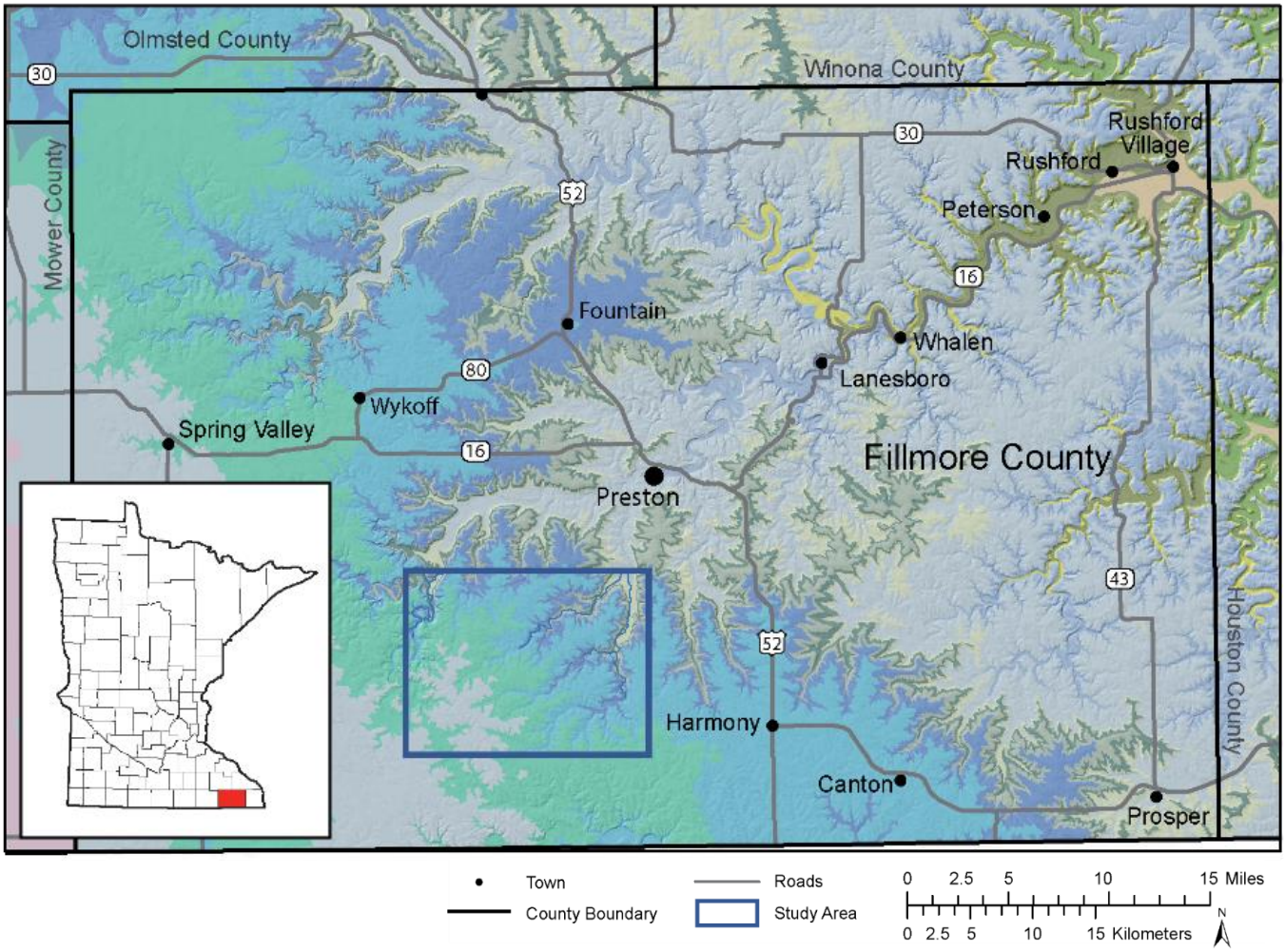

Figure 1. *Location map for the Crystal Creek study area. Geology base map shading corresponds with shading in in the Formation column of Figure 2.*

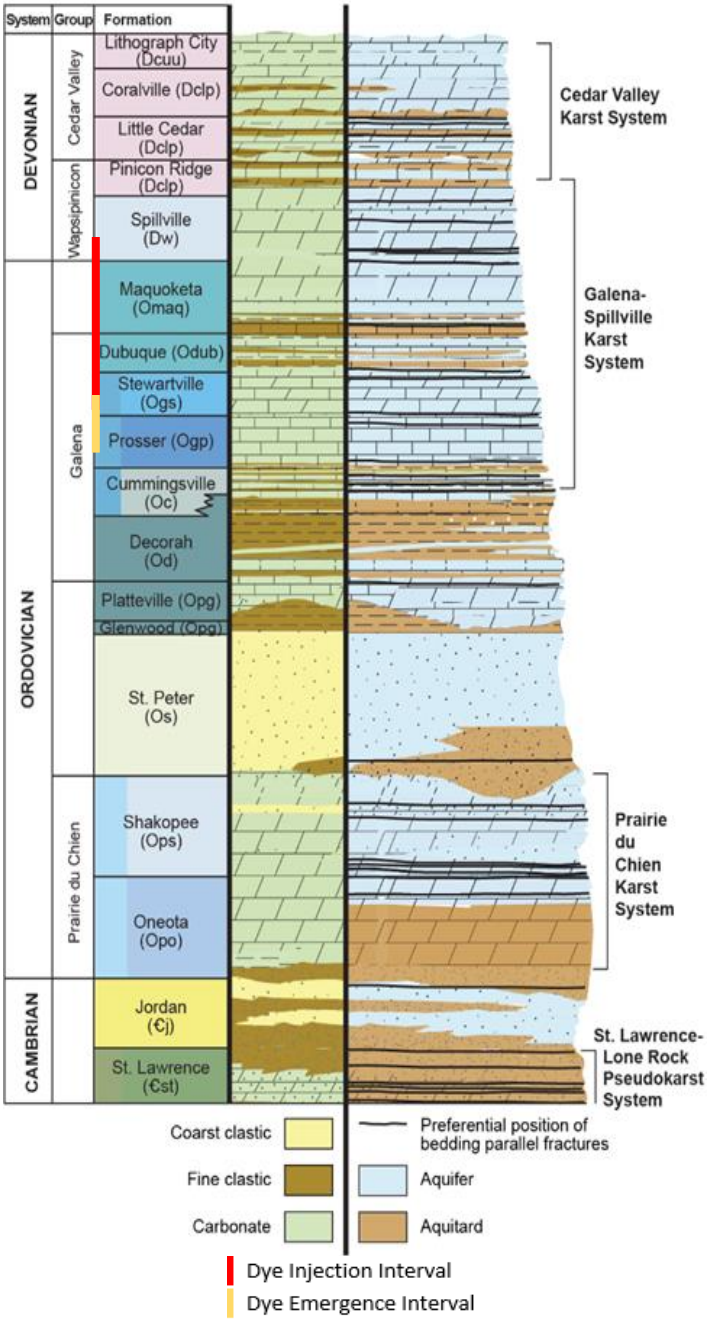

Figure 2. *Geologic and hydrogeologic attributes of Paleozoic rocks in southeastern Minnesota. Modified from Runkel et al. 2013.*

Fillmore County has abundant exposures of bedrock from Upper Cambrian through Devonian age capped by unconsolidated Cretaceous and Quaternary unconsolidated sediments such as loess, sand, and colluvium (Mossler, 1995). The surface topography is comprised of flat uplands plateaus mostly underlain by resistant limestones and dolostones of the Galena Group, Dubuque and Maquoketa Formations, and the Wapsipinicon and Cedar Valley Groups (Mossler and Hobbs, 1995). This upland landscape is dotted with sinkholes that drain through subsurface joints and conduits that have been enlarged by dissolution. Springs and groundwater seepage occurs along bluff walls and meander scars of St. Peter Sandstone, and the contact of the Platteville and Decorah Shale and the contact of the Prosser Limestone and Cummingsville Formation (Mossler and Hobbs, 1995, Steenberg et al., 2014). A generalized geologic stratigraphic column for Fillmore County (Figure 2) shows lithostratigraphic and generalized hydrostratigraphic properties for each of the units (modified from Runkel et. al. 2013). Hydrostratigraphic attributes have been generalized into either aquifer or aquitard based on their relative permeability. Layers assigned as aquifers are permeable and easily

transmit water through porous media, fractures or conduits. Layers assigned aquitard have lower permeability that vertically retards flow, effectively hydraulically separating aquifer layers. However, layers designated as aquitards may contain high permeability bedding plane fractures conductive enough to yield large quantities of water. The lower portion of the Galena-Spillville karst system (Figure 2) was examined in the current study, as dyes entered the Maquoketa, Dubuque and Stewartville formations and emerged near the Prosser-Cummingsville contact. Galena-Spillville karst generally has very rapid groundwater flow velocities, with dyes arriving within hours at discharge locations and being flushed from the flow system completely within days to weeks.

Methods

Dye tracing was accomplished with the use of fluorescent dyes to determine groundwater flow directions and estimates of travel times. The dyes were flushed into sinkholes with either 1,000 gallons of water or by utilizing snow melt running into sinkholes (Figure 3).

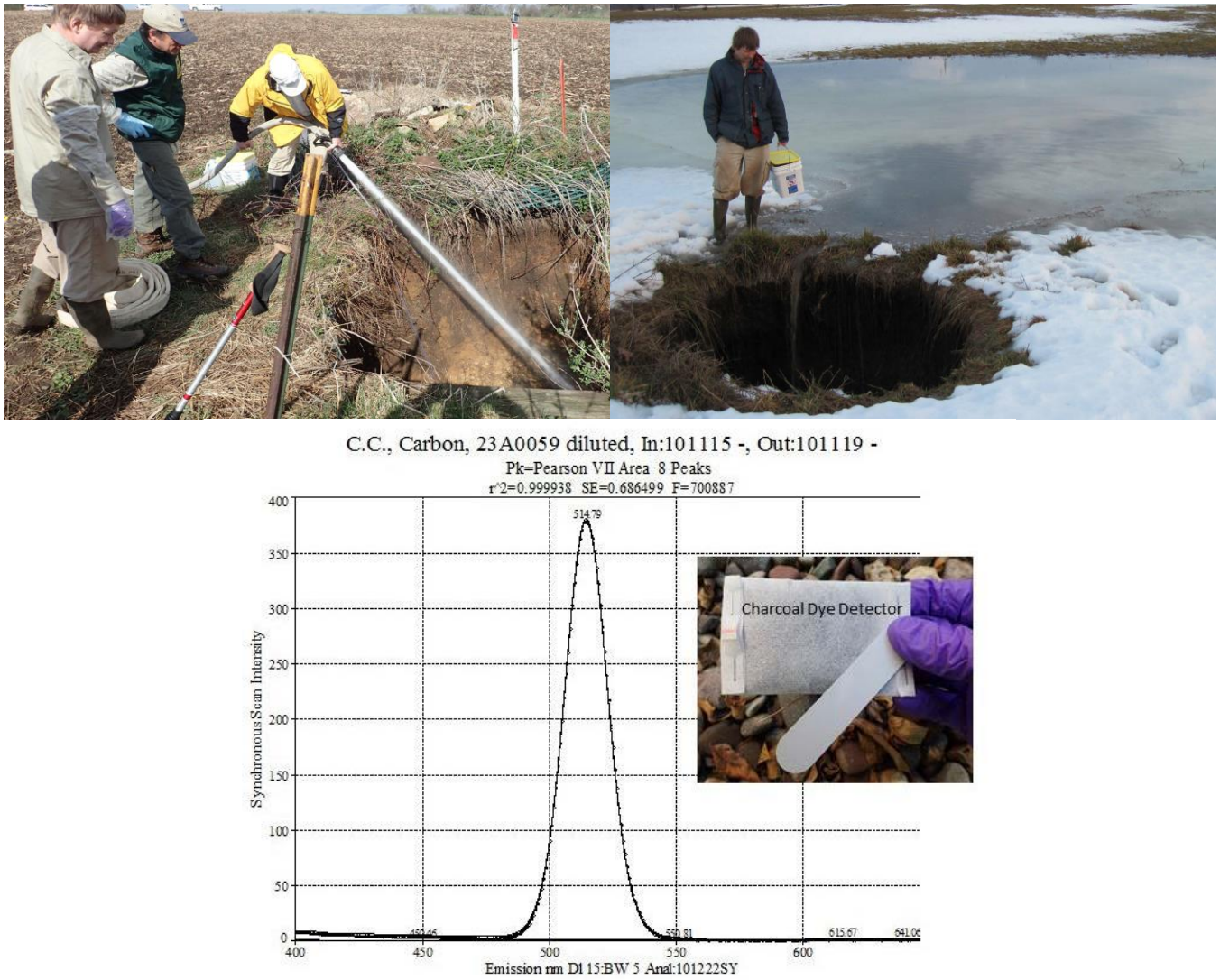

Figure 3. *Flushing dye into sinkhole using a 1,000 gallon tanker (top left) and natural flow from snowmelt (top right). The bottom image contains fluorescent spectrum results at Twin Springs in 2010 and an example charcoal detector (bug) used for analysis. The peak centered at ~515 nm indicates a positive Uranine recovery.*

Charcoal detectors, referred to as bugs, were placed at various spring and stream locations to absorb the fluorescent dyes. The locations of the dye input points and sampling locations are shown in Figure 4. Bugs were changed at various time intervals to allow bracketing the time it took for dye to arrive at the monitoring locations. Following removal from

the monitoring locations, the bugs were brought to the University of Minnesota Earth Sciences Department Hydrochemistry Laboratory for analysis. The bugs were bathed in a NaOH eluent solution that strips dye from the charcoal and the solution was analyzed with a scanning spectrofluorometer. Each dye is characterized by a unique emission wavelength. Figure 3 shows analysis results for Uranine recovery in the spring run of Twin Springs from Nov. 15 to Nov. 19, 2010.

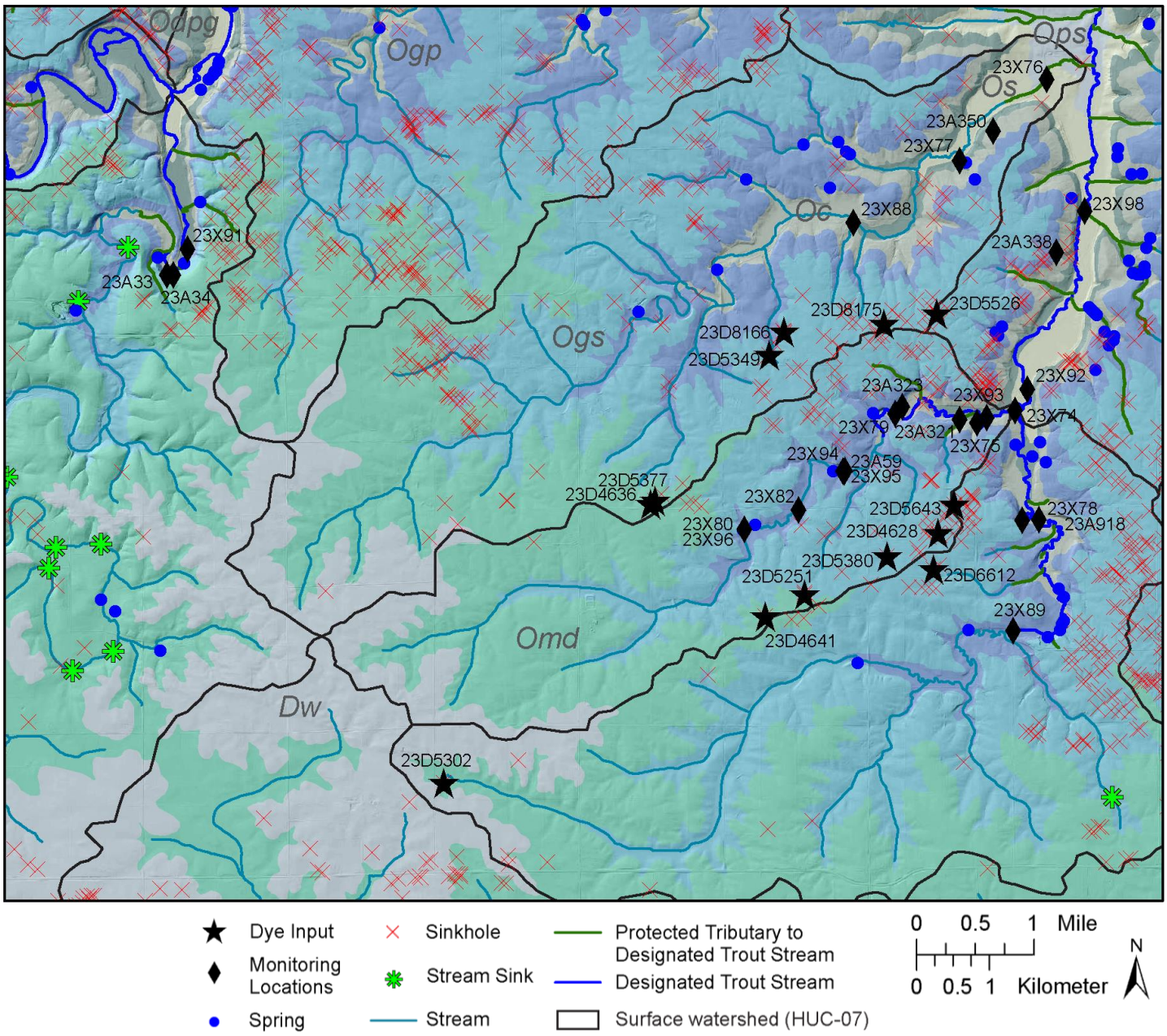

Figure 4. *Dye input points and sampling locations for the* 2010, 2011, 2013 and 2016 traces.

Results and Discussion

From 2010 through 2016, a total of 14 dye traces were conducted in the CCW. In 10 of 14 traces, a positive connection was confirmed between the sinkhole dye input and a monitored spring or creek location. Results from the dye traces are shown in Table 1 and Figures 5 and 6. Discussion related to these traces is broken down into three primary areas; Groundwater Springsheds, Groundwater Flow Direction and Velocity, and Chemical Indicators and Stratigraphy.

Trace #	Input date	Input Site ID	Dye	Detection Site	Groundwater Springshed
1	March 11, 2010	23D4628	UranHS	23A918	Willow Pond
2	March 11, 2010	23D5643	Eos	23A918	Willow Pond
3	July 20, 2010	23D5526	EranHS	23A323 and 23X79[1]	Trout Pond
4	July 20, 2010	23D8175	Eos	23A323 and 23X79[1]	Trout Pond
5	November 15, 2010	23D5251	UranC	23X94 (spring 23A59)	Twin Springs
6	March 17, 2011	23D5380	Eos	Non-detection	---
7	November 3, 2011	23D5349	RhWT	23X93[2]	Trout Pond
8	November 3, 2011	23D5377	UranHS	Non-detection	---
9	November 3, 2011	23D5380	Eos	23X74[3]	Willow Pond
10	March 9, 2013	23D6612	RhWT	Non-detection	---
11	March 9, 2013	23D8166	Eos	Non-detection	---
12	March 30, 2013	23D4641	UranHS	23X96 (spring 23A28 and 23X94 (spring 23A59)	Crystal Spring and Twin Springs
13	April 21, 2016	23D5302	UranC	23A33 and 23A34	Starless River
14	April 21, 2016	23D4636	Eos	23X96 (spring 23A28) and 23X94 (spring 23A59)	Crystal Spring and Twin Springs

Table 1: *Dye trace summary for Crystal Creek Watershed Area. More detailed results can be found in Table Appendices.*

[1] Site 23X79 is on Crystal Creek, upstream of spring 23A323. The actual emergence(s) may be from spring(s) 23A322 and/or other spring(s) yet unidentified

[2] Site 23X93 is on Crystal Creek at CCO. The actual emergence(s) may be from spring(s) 23A322, 23A323 and/or other spring(s) yet unidentified

[3] Site 23X74 is on Willow Creek, upstream of the confluence with Crystal Creek. The actual emergence(s) may be from spring(s) 23A918 and/or other spring(s) yet unidentified

Groundwater Springsheds

These traces began the process of delineating the boundaries for five springsheds: Starless River, Crystal Spring, Twin Springs, Trout Pond and Willow Pond (Figures 5 and 6). The delineated springshed boundaries show that surface watersheds and groundwatersheds in the CCW and vicinity are not congruent. For example, about 49 ha (120 acres) of the springshed for Trout Pond spring is located outside of the CCW surface watershed boundary. Conversely, trace results for the Willow Pond springshed document groundwater flowpaths originating in CCW that connect to springs located outside of the CCW surface watershed. This suggests that agricultural related nutrient applications in this particular area (covering about 10 ha (25 ac)) may not be contributing to nitrate loading in the CCW as monitored at the Crystal Creek outlet. The far upstream southwest part of CCW may also serve as recharge areas for springs outside of CCW, but more traces are needed to confirm the springshed boundaries. This suggestion is based on the location and flow directions of the groundwatershed delineated for the Starless River Springshed (Figure 6).

Groundwater Flow Direction and Velocity

Groundwater flow velocities in the Galena group can be extremely rapid and conduit pathways can extend for several miles (Alexander and others, 1996, Mohring, 1983). Groundwater velocities for the Twin Springs springshed during a 2011 trace were at least 2.4 kilometers/day (1.5 miles/day). This velocity is consistent with the range of peak groundwater flow velocities (1.6-4.8 km/day, 1-3 miles/day) from previous traces conducted in the Spillville-Galena Karst (Green and others, 2014). The longest flow path in this set of traces was 8.0 km (5 miles), while the shortest was .64 km (0.4 miles).

Chemical Indicators and Stratigraphy

Figure 7 graphically represents the stratigraphy of the CCW area and schematically represents dye trace vectors in cross section view. The illustration shows dye flow along hypothetical conduits in the Maquoketa, Dubuque, Stewartville, and Prosser Formations. Vertical fractures are densely distributed in shallow bedrock (within 15 m of bedrock surface) conditions (Runkel et al. 2003, Runkel et al. 2006). The figure also shows average monthly nitrate-nitrogen concentrations collected at monitoring stations in the CCW from 2010 to 2016.

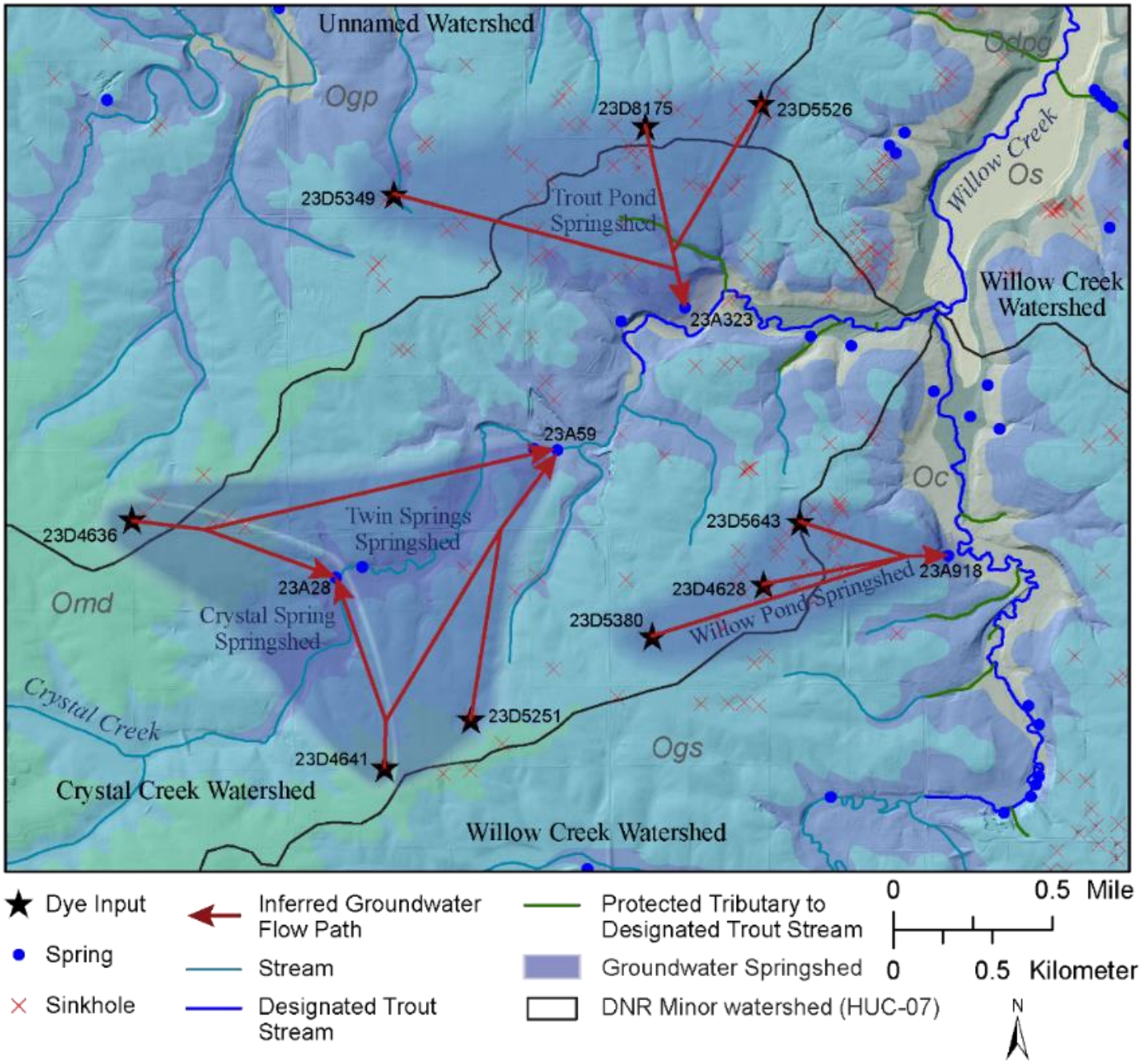

Figure 5. *Inferred groundwater flow paths and delineated groundwater springsheds for the Crystal, Twin, Willow, and Trout Springsheds.*

Elevated levels of nitrate-nitrogen can be used as a geochemical indicator of recent human influences on groundwater. Nitrate-nitrogen concentrations greater than 1 part per million are greater than background conditions and possibly indicate that an aquifer has been impacted by activities on the land surface (Minn. Dept. of Health, 1998 and Wilson, 2012). Nitrate-nitrogen concentrations greater than 3 ppm indicate that an aquifer has been impacted by activities on the land surface (Minn. Dept. of Health, 1998).

Nitrate-nitrogen collected in the CCW shows elevated levels at the springs and stations monitored along Crystal Creek. Average nitrate-nitrogen concentrations collected at Crystal Spring and Twin Springs show relatively high levels of 16.8 ppm and 14.0 ppm, respectively. These concentrations are consistent with local row cropping systems with sub-surface tile drainage at four-foot depth. The high nitrate levels in the springs indicate direct connections of surface water and groundwater and oxidized conditions in the water table. They are additionally consistent for areas of southeastern Minnesota where the overlying Maquoketa and Dubuque aquitard has been breached by erosion and vertical fractures

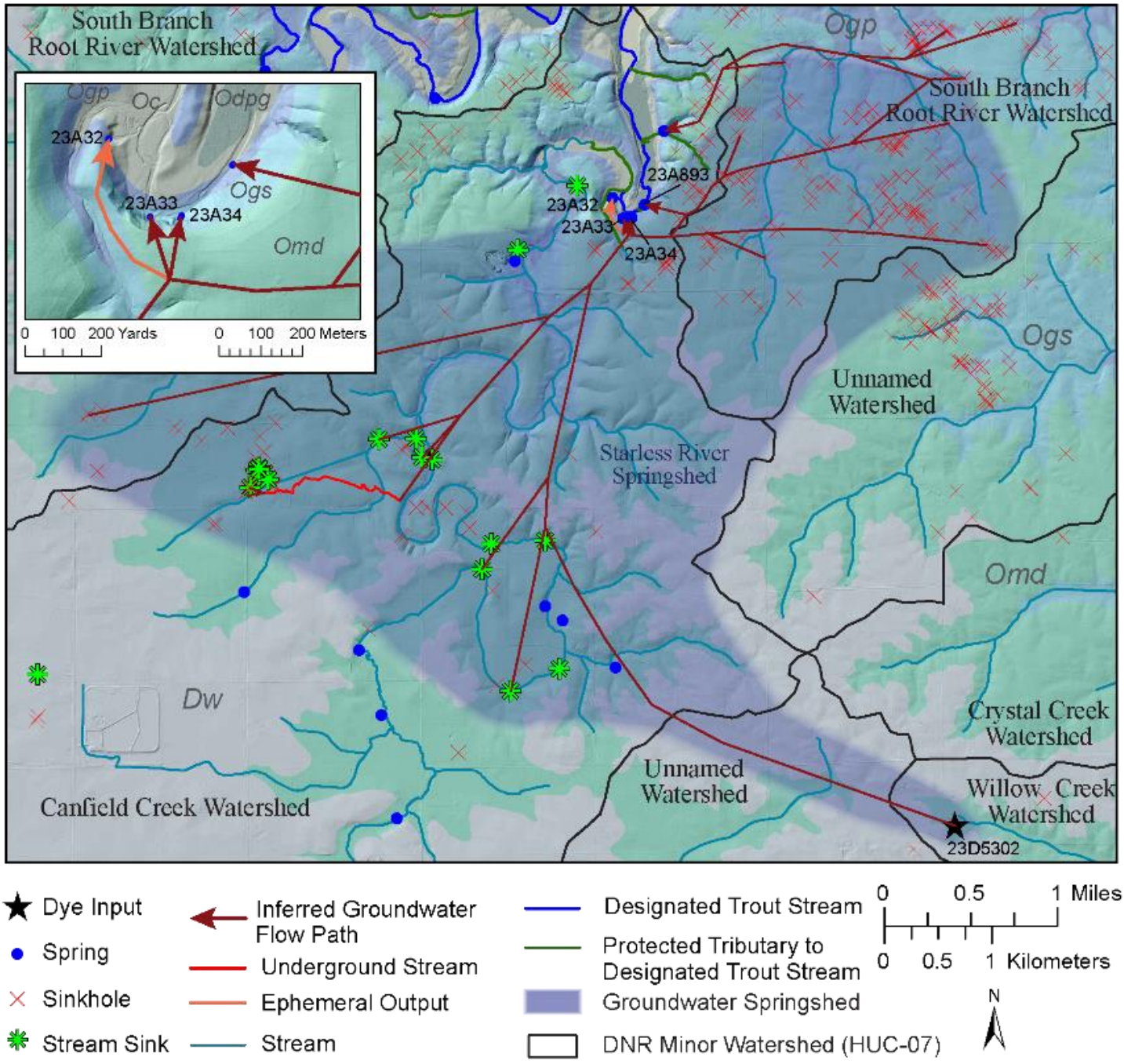

Figure 6. *Inferred groundwater flow paths and aerial extent of the Starless River Springshed.*

(Steenberg et al., 2014). The 7.7 ppm nitrate-nitrogen value collected at the station labeled Crystal Creek is slightly enigmatic. It is possible that the lower average nitrate-nitrogen concentration found at this location is from nitrate poor water preferentially flowing from areas up-gradient where the overlying Maquoketa and Dubuque aquitard is not breached. Additional nitrate poor water appears to enter Crystal Creek in its lower reaches from regional sources located below the Cummingsville-Decorah-Platteville-Glenwood aquitard system (Runkel et al., 2014). This water has a dilution effect on the average stream nitrate-nitrogen level lowering the average nitrate-nitrogen concentration to 9.5 and 9.1 ppm respectively at the Crystal Creek Outlet and Willow Creek at Jumper Road stations. The observed pattern of high nitrate levels in surface water and upper bedrock aquifers and nitrate poor water in lower units is a regional phenomenon recently observed by Runkel and others (Runkel et al., 2014). It is likely that without the buffering effect caused by regional nitrate-poor water, nitrate concentrations would be considerably higher in cold water trout streams

like Crystal Creek. This highlights the importance of minimizing nitrate leaching losses through the proactive use of nitrogen best management practices on cropland to minimize further contamination of both shallow and deep aquifers.

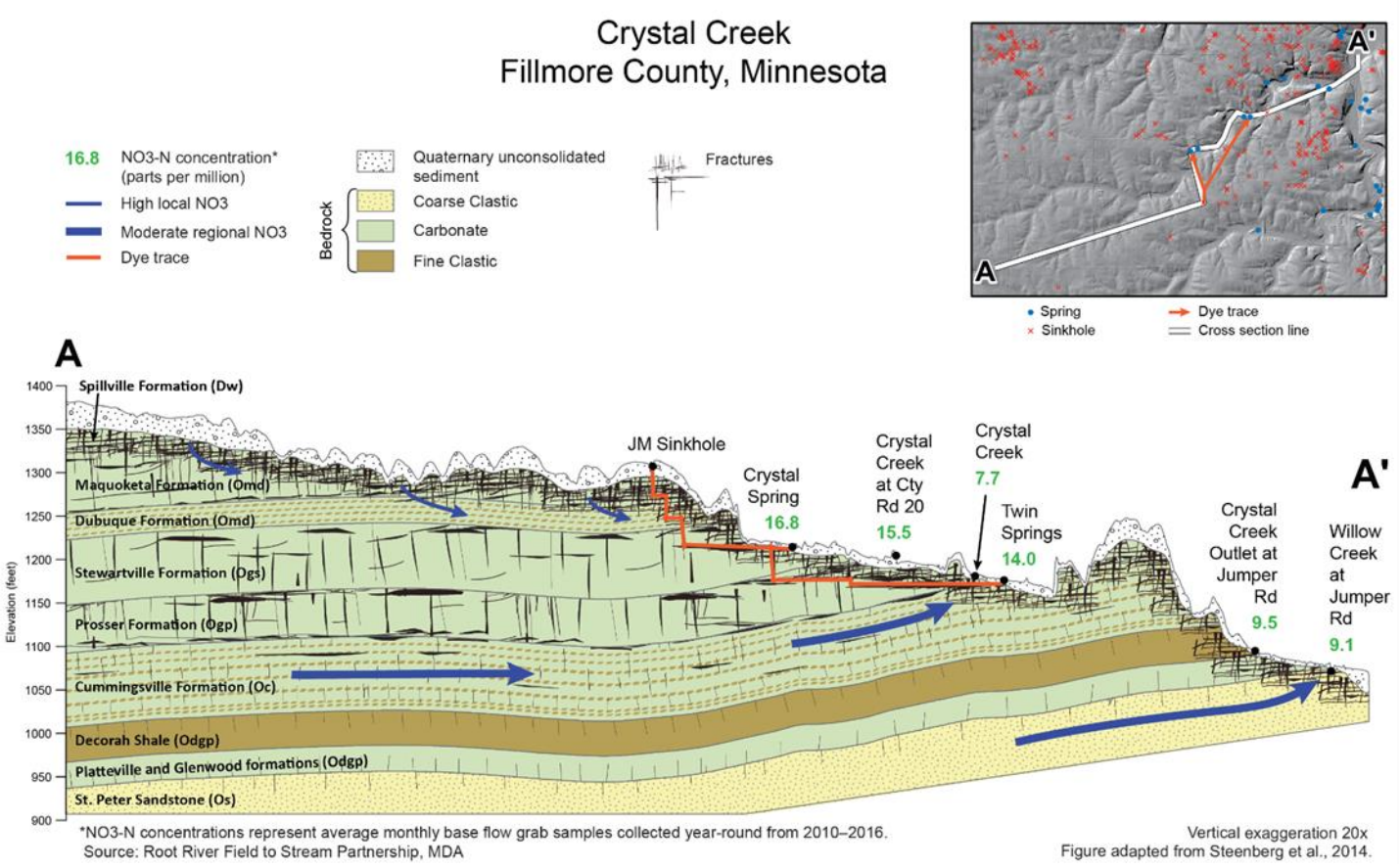

Figure 7. *Hydrogeologic cross section of the Crystal Creek Watershed, highlighting dye trace from the southern half of the Twin Springs Springshed. Orientation of the cross section line is shown in inset map.*

Conclusions

These successful traces expanded and refined the boundaries of the springsheds feeding springs 23A0000028 (Crystal Spring), 23A0000032 (Deep Lake Spring; Starless River Springshed), 23A0000033 (Canfield Big Spring; Starless River Springshed), 23A0000034 (Black Rock Spring; Starless River Springshed), 23A0000059 (Twin Springs), 23A0000323 (Trout Pond Spring), and 23A0000918 (Gatzke Spring; Willow Pond Springshed) (Figures 5 & 6). The lateral extent of these springsheds are not sharp boundaries and can move dynamically, both horizontally and vertically, in response to changes in groundwater levels. These refined springshed maps help improve nitrate-nitrogen yield loss computations and computer models used to measure the effectiveness of nitrogen practices. They are also informative in determining where nitrogen management surveys and BMPs should be concentrated. More importantly, the dye trace and resulting hydrologic cross section maps will add value in helping educate landowners and farmers about the direct link between nitrogen management practices and groundwater. Additional dye trace studies are planned in future years to further refine springshed boundaries and help improve the understanding of complex surface water-groundwater interactions in the CCW.

Acknowledgments

This project would not have been possible without the cooperation of over 20 landowners and farmers in and around the project study area and the Preston Volunteer Fire Department. Staff from the Fillmore Soil and Water Conservation

District were instrumental in helping collect dye trace packets throughout the six-year study. Funding for this project was provided by the Minnesota Clean Water Land and Legacy Amendment and the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). Additional thanks is given to Julia Steenberg for assistance in developing the geologic cross section and for discussion on area groundwater flow and nitrate transport. Holly Johnson provided graphical editing assistance in developing the geologic cross section.

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Crystal Creek Dye Traces - 11 Mar, 20 Jul and 15 Nov 2010 (5 Traces)

Dye Trace 1 of 11 Mar 2010: Dye input into Scheevel Sinkhole (MN23:D04628, 571,095 E / 4,825,343 N, NAD 83, Zone 15): poured 787.83 g **Uranine HS** (35 weight % solution) at 16:53.

Dye Trace 2 of 11 Mar 2010: Dye input into Kriegel Sinkhole (MN23:D05643, 571,276 E / 4,825,659 N, NAD 83, Zone 15): poured 1037.23 g **Eosine** (33 weight % solution) at 17:40.

Dye Trace 1 of 20 July 2010: Dye input into Unnamed Sinkhole (MN23:D05526, 571,080 E / 4,827,781 N, NAD 83, Zone 15): poured 324.12 g **Uranine HS** (35 weight % solution) at 16:25.

Dye Trace 2 of 20 July 2010: Dye input into Kruegel Sinkhole (MN23:D08175, 570,495 E / 4,827,665 N, NAD 83, Zone 15): poured 310.15 g **Eosine** (33 weight % solution) at 17:56.

Dye Trace of 15 November 2010: Dye input into Kent Dornink Sinkhole Middle (MN23:D05251, 569,609 E / 4,824,657 N, NAD 83, Zone 15): poured 313.36 g **Uranine C** (35 weight % solution) at 15:32.

Field Personnel at Input and/or Sampling: Kevin J. Kuehner, Jeffrey A. Green

Lab Personnel: Andrew Luhmann, Su Yi Chai, Betty J. Wheeler, E. Calvin Alexander, Jr.

Carbon (Bug) Analysis Results

Site Code	Site Name	KFD # s	UTMs NAD 83, Zone 15		CC1	11 Mar 2010 Dye Input	CC2	CC3	CC4	CC5	20 Jul 2010 Dye Input	CC6	CC7	CC8	CC9	CC10	15 Nov 2010 Dye Input	CC11	CC12	CC13
			Easting	Northing	5 Mar to 11 Mar 2010		xx Mar to 18 Mar 2010	18 Mar to 29 Mar 2010	29 Mar to 13 Apr 2010	13 Apr to 5 May 5 2010		19 Jul to 26 Jul 2010	26 Jul to 2 Aug 2010	2 Aug to 9 Aug 2010	9 Aug to 20 Aug 2010	10 Nov to 15 Nov 2010		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010
C1	**C1 Crystal Spring Bug Set** (associated with Crystal Spring 23A28)	**23X96**	568,940	4,825,385	**nd**		**nd** (in: 10 Mar)	**nd**	**nd**	**nd**						Uran* (3.0 σ)		Uran* (6.3 σ)	Uran* (3.0 σ)	SrB* (4.7 σ)
C1A	**C1A - Co. 20 Crystal Creek Crossing**	**23X82**	569,541	4,825,598												**nd**		**nd**	**nd**	**nd**
C2	**C2 Crystal Creek Bug Set** (aka, Scheevel-Frank upstream)	**23X95**	570,032	4,826,025			**nd** (in: 11 Mar)	**nd**	**nd**	**nd**			**nd**	**nd**	**nd**	**nd**		Uran* (3.5 σ)	**nd**	**nd**

Crystal Creek Dye Traces - 11 Mar, 20 Jul and 15 Nov 2010 (continued - 2)

Site Code	Site Name	KFD # s	UTMs NAD 83, Zone 15		CC1	11 Mar 2010 Dye Input	CC2	CC3	CC4	CC5	20 Jul 2010 Dye Input	CC6	CC7	CC8	CC9	CC10	15 Nov 2010 Dye Input	CC11	CC12	CC13
			Easting	Northing	5 Mar to 11 Mar 2010		xx Mar to 18 Mar 2010	18 Mar to 29 Mar 2010	29 Mar to 13 Apr 2010	13 Apr to 5 May 5 2010		19 Jul to 26 Jul 2010	26 Jul to 2 Aug 2010	2 Aug to 9 Aug 2010	9 Aug to 20 Aug 2010	10 Nov to 15 Nov 2010		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010
C3	**C3 Bug Set: A59 Spring Run** (aka, Scheevel-Frank Spgs Combined)	23X94	570,053	4,826,033			nd (in: 11 Mar)	nd	nd	nd		nd	nd	nd	nd	Uran* (10 σ)		Uran (552 σ) (diluted)	Uran (179 σ)	Uran (9.1 σ)
C4	**C4 Unnamed Spring** (aka, 23A321)	23A321	571,331	4,826,600			nd (in: 8 Mar)	nd	(empty)	nd										
C5	**CCO Bug Set** (aka, Crystal Creek Outlet) (aka, C5 Crystal Creek Mon. Station)	23X93	571,635	4,826,625	nd		nd (in: 11 Mar)	nd	Eos* (5.9 σ)	nd		Uran (110 σ), Eos (21 σ)	Uran (39 σ), Eos (7.6 σ)	Uran (16 σ), Eos (6.9 σ)	nd	nd		Uran	Uran (44 σ)	Uran (7.9 σ)
C5A	**C5A Bug Set** (associated with spring 23A320)	23X75	571,527	4,826,563				nd	nd	nd										
C6	**C6 Willow Creek Bug Set** (upstream of confluence with Crystal Creek)	23X74	571,952	4,826,700			Uran (96 σ), Eos (5.3 σ) (in: 12 Mar)	Uran (7.6 σ)	Uran (10 σ), Eos (11 σ)	Eos (5.4 σ)						Eos* (3.3 σ)		Eos* (6.6 σ)	nd	nd
C7	**C7 Gatzke Spring** (aka, Big Pond Spring)	23A918	572,029	4,825,486			Uran (303 σ), Eos (43 σ) (diluted) (in: 11 Mar)	Uran (192 σ), Eos (12 σ)	Uran (188 σ), Eos (13 σ)	Uran (43 σ), Eos (5.6 σ)										

Crystal Creek Dye Traces - 11 Mar, 20 Jul and 15 Nov 2010 (continued - 3)

Site Code	Site Name	KFD # s	UTMs NAD 83, Zone 15		CC1	11 Mar 2010 Dye Input	CC2	CC3	CC4	CC5	20 Jul 2010 Dye Input	CC6	CC7	CC8	CC9	CC10	15 Nov 2010 Dye Input	CC11	CC12	CC13
			Easting	Northing	5 Mar to 11 Mar 2010		xx Mar to 18 Mar 2010	18 Mar to 29 Mar 2010	29 Mar to 13 Apr 2010	13 Apr to 5 May 2010		19 Jul to 26 Jul 2010	26 Jul to 2 Aug 2010	2 Aug to 9 Aug 2010	9 Aug to 20 Aug 2010	10 Nov to 15 Nov 2010		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010
C8	**Willow-Gatzke Bug Set** (on Willow Creek upstream of Gatzke Spring) (aka, C8)	**23X78**	572,217	4,825,489			Uran * (13 σ) (in: 11 Mar)	nd	nd	nd										
C9	**Upper Willow Creek** (271st Ave. crossing Willow Creek) (aka, Willow Upstream)	**23X89**	571,927	4,824,259				Uran* (8.5 σ), Eos* (4.3 σ)	nd	nd						nd		Uran* (3.7 σ)	nd	
---	**Noel Frank Trout Pond Spring** (aka, Spring 23A323)	**23A323**	570,694	4,826,748								Uran (184 σ), Eos (41 σ) (diluted)	Uran (285 σ), Eos (22 σ) (diluted)	nd	Uran (216 σ), Eos (12 σ)					
---	**A323 Upstream Bug Set** (upstream of Spring 23A323)	**23X79**	570,612	4,826,663								Uran [2] (14 σ), Eos [1] (21 σ)	nd	no data (lab mistake)	nd					
---	**Unnamed Spring** (aka, 23A338)	**23A338**	572,410	4,828,459								nd	nd	nd	nd					
---	**Bug Set for 23A348 / 23A349**	**23X77**	571,331	4,829,479								Uran* (4.0 σ)	nd	nd	nd					

Crystal Creek Dye Traces - 11 Mar, 20 Jul and 15 Nov 2010 (continued - 4)

Site Code	Site Name	KFD # s	UTMs NAD 83, Zone 15		CC1	11 Mar 2010 Dye Input	CC2	CC3	CC4	CC5	20 Jul 2010 Dye Input	CC6	CC7	CC8	CC9	CC10	15 Nov 2010 Dye Input	CC11	CC12	CC13
			Easting	Northing	5 Mar to 11 Mar 2010		xx Mar to 18 Mar 2010	18 Mar to 29 Mar 2010	29 Mar to 13 Apr 2010	13 Apr to 5 May 5 2010		19 Jul to 26 Jul 2010	26 Jul to 2 Aug 2010	2 Aug to 9 Aug 2010	9 Aug to 20 Aug 2010	10 Nov to 15 Nov 2010		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010
---	**Unnamed Spring** (aka, 23A350)	**23A350**	571,702	4,829,805								nd	nd	nd	nd					
Hwy15	**Highway 15 East Bug Set** (on unnamed creek)	**23X88**	570,152	4,828,791								Uran* (5.2 σ)	Uran* (3.8 σ)	nd	nd					
---	**Highway 22 North Bug Set** (unnamed creek crossing)	**23X76**	572,302	4,830,383								nd	Uran* (3.9 σ)	nd	nd					
---	**Co. 22 Willow Creek Crossing** (aka, Highway 22 South) (aka, Hwy 22 monitoring site)	**23X98**	572,722	4,828,920								Uran (47 σ), Eos (7.9 σ)	Uran (4.0 σ)	nd	Eos (9.7 σ)					

nd	indicates no dye detected
	(yellow cell) indicates no bug was received by the lab
empty	indicates no charcoal remained in the bug, as received by the lab
Eos	indicates Eosine dye detected
Eos [1]	indicates Eosine dye detected; not confirmed but may be correct (upstream spring 23A322 was not monitored)
RhWT	indicates Rhodamine WT detected (confirmed; may be from an upstream source not monitored)
Uran	indicates Uranine (fluorescein) dye detected
Uran [2]	indicates Uranine (fluorescein) dye detected; not confirmed but may be correct (upstream spring 23A322 was not monitored)
Eos *	indicates Eosine to low to quantify or from some other unknown source
SrB *	indicates Sulforhodamine B too low to quanitify or from some other unknown source
Uran *	indicates Uranine (fluorescein) too low to quantify or from some other unknown source

Crystal Creek 17 March and 3 November 2011 Traces (4 Traces)

Dye Trace of 17 Mar 2011: Dye input into Dave/Tracie Mensink Sinkhole 6 (MN23:D05380) (570,528 E / 4,825,079 N, NAD 83, Zone 15): poured 548.92 g **Eosine** (33 weight % solution) at 13:28.

Dye Traces of 3 Nov 2011:

Dye Trace 1: Dye input into Dave Scheevel Sinkhole 7 (MN23:D05349, 569,220 E / 4,827,321 N , NAD 83, Zone 15): poured 960.9 g **Rhodamine WT** (17.7 weight % solution) at 14:22.

Dye Trace 2: Dye input into Jerome O'Connor Sinkhole 8 (MN23:D05377, 567,949 E / 4,825,699 N, NAD 83, Zone 15): poured 921 g **Uranine HS** (35 weight % solution) at 15:05.

DyeTrace 3: Dye input into Dave/Tracie Mensink Sinkhole 6 (MN23:D05380, 570,528 E / 4,825,079 N, NAD 83, Zone 15): poured 532 g **Eosine** (33 weight % solution) at 16:00.

Field Personnel at Input and/or Sampling: Kevin J. Kuehner, Jeffrey A. Green, Joe Magee and Jennifer Ronnenberg

Lab Personnel: Su Yi Chai, Joel T. Groten, W. Travis Garmon, Betty J. Wheeler, E. Calvin Alexander, Jr.

Charcoal (Bug) Analysis Results

Site Code	Field Name	KFD #	UTMs NAD 83, Zone 15		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010	17 March 2011 Dye Input	16 Mar to 25 Mar 2011	25 Mar to 5 Apr 2011	3 Nov 2011 Dye Input	8 Nov to 17 Nov 2011	17 Nov to 15 Dec 2011	15 Dec 2011 to 24/26 Jan 2012	24/26 Jan to 21 Feb 2012	21 Feb to 19 Mar 2012	19 Mar to 19 Apr 2012	19 Apr to 15 May 2012
			Easting	Northing														
C1	**C1 Crystal Spring Bug Set** (associated with Crystal Spring 23A28)	**23X96**	568,940	4,825,385	Uran* (6.3 σ)	Uran* (3.0 σ)	SrB* (4.7 σ)		Uran* (5.3 σ)	Uran* (6.2 σ)			**nd**	**nd** (out: 26 Jan 2012)	**nd** (in: 26 Jan 2012)	**nd**	**nd**	**nd**
C1A	**C1A - Co. 20 Crystal Creek Crossing**	**23X82**	569,541	4,825,598	**nd**	**nd**	**nd**		Uran* (5.4 σ)	Uran* (4.2 σ)								
C2	**C2 Crystal Creek Bug Set** (aka, Scheevel-Frank upstream)	**23X95**	570,032	4,826,025	Uran* (3.5 σ)	**nd**	**nd**		Uran* (5.6 σ)	Uran* (3.0 σ)			**nd**	**nd** (out: 26 Jan 2012)	**nd** (in: 26 Jan 2012)	**nd**	**nd**	**nd**
C3	**C3 Bug Set: A59 Spring Run** (aka, Scheevel-Frank Springs Combined)	**23X94**	570,053	4,826,033	Uran (552 σ) (diluted)	Uran (179 σ)	Uran (9.1 σ)		Uran (16 σ)	Uran (14 σ)			**nd**	**nd** (out: 26 Jan 2012)	**nd** (in: 26 Jan 2012)	**nd**	**nd**	**nd**

Crystal Creek 17 Mar and 3 Nov 2011 Traces (continued)

Site Code	Field Name	KFD #	UTMs NAD 83, Zone 15		15 Nov to 19 Nov 2010	19 Nov to 29 Nov 2010	29 Nov to 8 Dec 2010	17 March 2011 Dye Input	16 Mar to 25 Mar 2011	25 Mar to 5 Apr 2011	3 Nov 2011 Dye Input	8 Nov to 17 Nov 2011	17 Nov to 15 Dec 2011	15 Dec 2011 to 24/26 Jan 2012	24/26 Jan to 21 Feb 2012	21 Feb to 19 Mar 2012	19 Mar to 19 Apr 2012	19 Apr to 15 May 2012
			Easting	Northing														
C5	**CCO Bug Set** (aka, Crystal Creek Outlet) (aka, C5 Crystal Creek Mon. Station)	23X93	571,635	4,826,625	nd	Uran (44 σ)	Uran (7.9 σ)		Uran (8.9 σ)	nd		Eos * (3.2 σ) RhWT (144 σ)	RhWT (75 σ)	RhWT (17 σ) (out: 24 Jan 2012)	Uran * (4.8 σ) RhWT (3.5 σ) (in: 24 Jan 2012)	nd	nd	nd
C6	**C6 Willow Creek Bug Set** (upstream of confluence with Crystal Creek) (aka, Willow Creek Outlet or WCO)	23X74	571,952	4,826,700	Eos* (6.6 σ)	nd	nd		Eos * (5.4 σ)	nd			Eos (19 σ)	nd (out: 24 Jan 2012)	nd (in: 24 Jan 2012)	nd	nd	nd
C9	**Upper Willow Creek** (271st Ave. crossing Willow Creek) (aka, Willow Upstream)	23X89	571,927	4,824,259	Uran* (3.7 σ)	nd			Uran (8.8 σ)				nd		nd (in: 26 Jan 2012)	(empty)	nd	nd
Hwy15	**Highway 15 East Bug Set** (on unnamed creek)	23X88	570,152	4,828,791									nd		RhWT * (4.8 σ) (in: 26 Jan 2012)	nd	nd	nd
														nd (in: 15 Dec 2011 out: 19 Mar 2012)				

nd indicates no dye detected

(yellow cell) indicates no bug was received by the lab

empty indicates no charcoal remained in the bug, as received by the lab

Eos indicates Eosine dye detected (not confirmed by a subsequent sample; but may be from an upstream source not monitored)

RhWT indicates Rhodamine WT detected (confirmed; may be from an upstream source not monitored)

Uran indicates Uranine (fluorescein) dye detected (note that these are all from a previous trace)

Eos * indicates Eosine to low to quantify or from some other unknown source

RhWT * indicates Rhodamine WT too low to quantify or from some other unknown source

SrB * indicates Sulforhodamine B too low to quanitify or from some other unknown source

Uran * indicates Uranine (fluorescein) too low to quantify or from some other unknown source

Crystal Creek 9 and 30 March 2013 (Snowmelt) Traces (3 Traces)

Dye Trace 1 of 9 Mar 2013: Dye input into Unnamed Sinkhole 1 (MN23:D06612, 571,045 E / 4,824,942 N, NAD 83, Zone 15): poured 526.46 g **Rhodamine WT** (20 weight % solution) at 14:58. Snowmelt was flowing at between 20-40 gpm. Dye was poured into the stream at the west end of the sinkhole. Water was disappearing under the snow, and flowing to the swallet.

Dye Trace 2 of 9 Mar 2013: Dye input into Unnamed Sinkhole 2 (MN23:D08166: 569,381 E / 4,827,576 N, NAD 83, Zone 15): poured 587.91 g **Eosine** (33 weight % solution) at 16:01. Snowmelt runoff was flowing in a stream into the swallet of the sinkhole. Dye was pou4ed into the swallet.

Due Trace of 30 Mar 2013: Dye input into John Mensink Sinkhole (MN23:D04641: 569,171 E / 4,824,413 N, NAD 83, Zone 15): poured 581.26 g **Uranine HS** (35 weight % solution) at 12:30.

Field Personnel at Input and/or Sampling: Kevin J. Kuehner, Jeffrey A. Green

Lab Personnel: Kelsi R. Ustipak, Peter Putzier, Alexa LaQua, Jacob Phipps, Betty J. Wheeler, E. Calvin Alexander, Jr.

Charcoal (Bug) Analysis Results

	Field Name	KFD #	Site Type	UTMs (NAD 83, Zone 15)		4 Mar to 8 Mar 2013	9 Mar 2013 Dye Input	8 Mar to 12 Mar 2013	12 Mar to 20 Mar 2013	30 Mar 2013 Dye Input	20 Mar to 2 Apr 2013	2 Apr to 16 Apr 2013	16 Apr to 7 May 2013
				Easting	Northing								
C1	**C1 Crystal Spring Bug Set** (associated with Crystal Spring 23A28)	**MN23:X00096** (associated with MN23:A00028)	spring run	568,940	4,825,385	**nd**		**nd**	**nd**		**nd**	Uran (385 σ) Eos * (7.0 σ)	Uran (73 σ)
C1S	**C1 Cistern Bug Set**	**MN23:X00080**	collecting cistern at spring	568,938	4,825,386								Uran (76 σ)
C1A	**C1A - Co. 20 Crystal Creek Crossing**	**MN23:X00082**	creek	569,541	4,825,598	**nd**		**nd**	**nd**		**nd**		Uran (69 σ)
C2	**Crystal Creek** (upstream of Scheevel / Frank Spring, 23A59)	**MN23:X00095**	creek	570,032	4,826,025	**nd**		**nd**	**nd**				Uran (51 σ)
C3	**C3 Bug Set: A59 Spring Run** (aka, Scheevel-Frank Springs Combined)	**MN23:X00094** (associated with MN23:A00059)	spring run	570,053	4,826,033	**nd**		**nd**	**nd**		Uran (9.6 σ)		Uran (61 σ)
C5	**CCO Bug Set** (aka, Crystal Creek Outlet or CCO) (aka, C5 Crystal Creek Monitoring Station)	**MN23:X00093**	creek	571,635	4,826,625	**nd**		**nd**	Eos * (3.1 σ)		**nd**	Uran (93 σ)	Uran (22 σ)

Crystal Creek 9 and 30 Mar 2013 (Snowmelt) Traces (continued)

	Field Name	KFD #	Site Type	UTMs (NAD 83, Zone 15)		4 Mar to 8 Mar 2013	9 Mar 2013 Dye Input	8 Mar to 12 Mar 2013	12 Mar to 20 Mar 2013	30 Mar 2013 Dye Input	20 Mar to 2 Apr 2013	2 Apr to 16 Apr 2013	16 Apr to 7 May 2013
				Easting	Northing								
C6	**C6 Willow Creek Bug Set** (upstream of confluence with Crystal Creek) (aka, Willow Creek Outlet or WCO)	MN23:X00074	creek	571,952	4,826,700				nd		Uran * (6.4 σ)	Uran * (6.3 σ)	Uran * (10 σ) Eos * (7.0 σ)
C9	**Upper Willow Creek** (271st Ave. crossing Willow Creek) (aka, Willow Upstream) (upstream of CCO)	MN23:X00089	creek	571,927	4,824,259	nd		nd			nd		
WCOJ	**Willow Creek Outlet** (on Jumper Road) (aka, WCO)	MN23:X00092	creek	572,085	4,826,940	nd		nd	nd		nd	Uran (14 σ)	nd
Hwy15	**Highway 15 East Bug Set** (on unnamed creek)	MN23:X00088	creek	570,152	4,828,791	nd		nd	nd			nd	nd

nd indicates no dye detected

(yellow cell) indicates no bug was received by the lab

Eos indicates Eosine dye detected

Uran indicates Uranine (fluorescein) dye detected

Eos * indicates Eosine to low to quantify or from some other unknown source

Uran * indicates Uranine (fluorescein) too low to quantify or from some other unknown source

Crystal Creek 21 April 2016 Traces (2 Traces)

Dye Trace 1 of 21 Apr 2016: Dye input into Holy Grail North Sinkhole (MN23:D05302) (565,598 E / 4,822,569 N ± 1.6 m; NAD 83, Zone 15): poured 1,136.27 g **Uranine HC** (35 weight % solution) at 9:55. Prewet with about 300 gal (1,136 liters) water, dye poured thru a 50 ft. trimmie line, followed by about 700 gal (2,650 liters).

Dye Trace 2 of 21 Apr 2016: Dye input into Roeloff Sinkhole (MN23:D04636) (567,897 E / 4,825,662 N ± 2.8 m; NAD 83, Zone 15): poured 1,166.3 g **Eosine** (33 weight % solution) at 11:23. Prewet with about 300 gal (1,136 liters) water, dye poured, followed by about 700 gal (2,650 liters).

Field Personnel at Inputs and/or Sampling: Kevin J. Kuehner, Jeffrey A. Green, John Barry, E. Calvin Alexander, Jr., Jennifer Ronnenberg, Caleb Fischer
Lab Personnel: Sophie M. Kasahara, Betty J. Wheeler, E. Calvin Alexander, Jr.

Carbon (Bug) Analysis Results

	Field Name	KFD #	Site Type	UTMs (NAD 83, Zone 15)		Background Initial Install Date to 29 Mar 16 where Initial Date = 25 Feb 16, or 26 Feb 16, or 3 Mar 16	29 Mar to 20 Apr 2016	Dye Input 21 Apr 2016	20 Apr to 25 Apr 2016	25 Apr to 2 May 2016	2 May to 9 May 2016	9 May to 16 May 2016	16 May to 31 May 2016
				Easting	Northing								
C1	**Crystal Spring (Run)** (down stream, off NE corner of bridge)	**MN23:X00096** (associated with MN23:A00028)	spring run	568,939	4,825,386	**nd** (in: 25-Feb-16)	**nd**		**Eos** (very small peak: 5 IU)	**Eos** (solid peak: 31 IU)	**Eos** (small peak: 15 IU)	**Eos** (trace: 3 IU)	**Eos** (trace: 3 IU)
C2	**Crystal Creek** (upstream of Scheevel / Frank Spring, 23A59)	**MN23:X00095**	creek	570,032	4,826,025	**nd** (in: 25-Feb-16)	**nd**		**Eos** (solid peak: 48 IU)	**Eos** (strong peak: 138 IU)	**Eos** (small, significant peak: 9 IU)	**Eos** (small, significant peak: 10 IU)	**(empty)**
C3	**Scheevel/Frank Spring (Run)**	**MN23:X00094** (associated with MN23:A00059)	spring run	570,053	4,826,036	**nd** (in: 25-Feb-16)	**nd**		**Eos** (small peak: 14 IU)	**Eos** (solid peak: 41 IU)	**nd**	**Eos** (trace: 3 IU)	**Eos** (solid peak: 36 IU)
C9	**Upper Willow Creek** (271st Ave. crossing Willow Creek) (aka, Willow Upstream)	**MN23:X00089**	creek	571,927	4,824,259	**nd** (in: 25-Feb-16)	**nd**		**nd**	**nd**	**nd**	**nd**	**nd**
CCO	**Crystal Creek Outlet** (at MDA monitor) (aka, C5)	**MN23:X00093**	creek	571,635	4,826,625	**nd** (in: 25-Feb-16)	**nd**		**nd**	**Eos** (solid peak: 26 IU)	**nd**	**nd**	**nd**
WCO	**Willow Creek Outlet** (on Jumper Road)	**MN23:X00092**	creek	572,085	4,826,940	**nd** (in: 26-Feb-16)	**nd**		**nd**	**Eos** (solid peak: 47 IU)	**nd**	**nd**	**nd**

Crystal Creek 21 Apr 2016 Traces (continued)

	Field Name	KFD #	Site Type	UTMs (NAD 83, Zone 15)		Background Initial Install Date to 29 Mar 16 where Initial Date = 25 Feb 16, or 26 Feb 16, or 3 Mar 16	29 Mar to 20 Apr 2016	Dye Input 21 Apr 2016	20 Apr to 25 Apr 2016	25 Apr to 2 May 2016	2 May to 9 May 2016	9 May to 16 May 2016	16 May to 31 May 2016
				Easting	Northing								
BRS	Black Rock Spring (in Forestville State Park)	MN23:A00034	spring	562,585	4,828,208	nd (in: 3-Mar-16)	nd		nd	Uran (strong peak: 91 IU)	Uran (solid peak: 35 IU)	Uran (solid peak: 49 IU)	Uran (strong peak: 57 IU)
CBS	Canfield Big Spring (in Forestville State Park)	MN23:A00033	spring	562,512	4,828,210	nd (in: 3-Mar-16)	nd		nd	Uran (small peak: 14 IU)	Uran (strong peak: 93 IU)	Uran (very strong peak: 314 IU)	Uran (very strong peak: 134 IU)
CAN	Canfield Creek (in Forestville State Park)	MN23:X00091	creek	562,745	4,828,493	(empty) (in: 3-Mar-16)	nd		nd	Uran (solid peak: 47 IU)	Uran (trace)	Uran (solid peak: 43 IU)	Uran (solid peak: 43 IU)
Hwy15	Unnamed Creek (at Co. Hwy 15 East)	MN23:X00088	creek	570,152	4,828,791	nd (in: 26-Feb-16)	nd		nd	nd	nd	nd	nd
ODS	Odessa Spring (Run) (convergence of 2 springs)	MN23:X00023	spring run	573,740	4,817,445	nd (in: 26-Feb-16)	nd		nd	Uran [1] (very small peak: 8 IU)	nd	nd	nd
UIT	Upper Iowa River at Trolley Site (upstream of Odessa Spring)	MN23:X00056	river	572,160	4,817,831	nd (in: 26-Feb-16)	nd		nd	nd	nd	nd	nd

nd indicates no dye detected

empty indicates no charcoal remained in the bug, as received by the lab

Eos indicates Eosine dye detected

Uran indicates Uranine (fluorescein) dye detected

Uran [1] indicates Uranine (fluorescein) dye detected; not confirmed by a subsequent sample

Summary Results of Crystal Creek Tracing 2010-2016

update: 17Mar2017

Trace #	Date	Input Site (KFD #)	Dye Used	Detection Site(s) (KFD #)	Springshed
1	11-Mar-2010	23D4628	UranHS	A918	Willow Pond Spring
2	11-Mar-2010	23D5643	Eos	A918	Willow Pond Spring
3	20-Jul-2010	23D5526	UranHS	A323	Trout Pond Spring
4	20-Jul-2010	23D8175	Eos	A323	Trout Pond Spring
5	15-Nov-2010	23D5251	UranC	X94 (A59)	Twin Springs
6	17-Mar-2011	23D5380	Eos	ND	---
7	3-Nov-2011	23D5349	RhWT	C5 CCO	Trout Pond Spring
8	3-Nov-2011	23D5377	UranHS	ND	---
9	3-Nov-2011	23D5380	Eos	C6 Willow Crk US	Willow Pond Spring
10	9-Mar-2013	23D6612	RhWT	ND	---
11	9-Mar-2013	23D8166	Eos	ND	---
12	30-Mar-2013	23D4641	UranHS	X96 (A28) X94 (A59)	Crystal Spring Twin Springs
13	21-Apr-2016	23D5302	UranC	A33 A34	Starless River
14	21-Apr-2016	23D4636	Eos	X96 (A28) X94 (A59)	Crystal Spring Twin Springs

ND **indicates no dye detected**

Eos **indicates Eosine dye detected**

RhWT **indicates Rhodamine WT detected**

Uran **indicates Uranine (fluorescein) dye detected**